

## Editorial

# Research and implementation needs to mitigate greenhouse gas emissions from agriculture in the USA

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**Abstract**

An urgent need exists to understand which agricultural land uses and land resource types have the greatest potential to mitigate greenhouse gas (GHG) emissions contributing to global change. Global change is a natural resource issue increasingly contributed to by human activities that now joins other important issues facing agricultural scientists, such as depletion of soil organic carbon (SOC), soil degradation and contamination, and pollution of natural waters by soil sediments and nutrients. Increasing demand for food by the growing global population is resulting in increased GHG emissions, soil disturbance, fossil fuel consumption to produce agricultural products, and biomass burning. To address these issues and the threat of accelerated GHG emissions, this paper addresses: (1) current scientific facts about the attributes of soil and natural resources, (2) strategies for sustainable use of our finite, non-renewable, and fragile land resources, and (3) advances made by agricultural sciences and their potential role in forming policy.

Site-specific adaptation of appropriate conservation technologies will be needed for sequestering SOC and reducing nitrous oxide (N<sub>2</sub>O) emission. Adoption of improved conservation technologies to mitigate GHG emission should consider: (i) the rate of C sequestration or GHG mitigation, (ii) the price offered for adopting various practices, (iii) the ease with which producers and land managers can alter land use and management activities, (iv) the potential impacts of targeting regions or practices, (v) the ancillary benefits to soil, water and air quality upon adoption of practices to sequester SOC or mitigate GHG emission, and (vi) the effectiveness and efficiency of various policies.

Development of improved conservation technologies to reduce GHG emissions could become part of more comprehensive conservation programs aimed at environmental protection, food security, and agricultural sustainability. An overarching research need is to determine the multiple benefits and trade-offs of improved conservation technologies so that land managers can systematically meet production and environmental goals and so that the most effective policies can be devised.

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**Keywords:** Soil organic C; Nitrous oxide; Greenhouse gas mitigation; Agricultural management

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**1. Introduction**

The scientific community is concerned about greenhouse gases (GHGs), because of the potential of GHGs to affect global climate. There is a need to know which land uses or land resource types have the greatest potential to emit and mitigate the three primary GHGs associated

with agriculture [carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), and methane (CH<sub>4</sub>)]. It is important that all three gases be investigated together to arrive at a verifiable estimate of net global warming potential. The issues raised in this paper are of particular importance to CO<sub>2</sub>, the largest contributor to atmospheric change, and N<sub>2</sub>O, the most potent gas affecting global warming potential.

The relatively recent enrichment of atmospheric CO<sub>2</sub> concentration of about 90 ppmv (from 280 ppmv in circa 1850–374 ppmv in 2003, representing 3.3 Pg CO<sub>2</sub> year<sup>-1</sup>) (WDCGG, 2004) can be partly linked to past agricultural activities. Until the 1950s, as much as 75% of the annual increase in atmospheric CO<sub>2</sub> concentration came from changes in land use, agricultural expansion, and soil cultivation. From the 1950s until the 1970s, >50% of the annual increase came from changes in land use, agricultural expansion into natural ecosystems, and mineralization of SOC. In the 1990s, ≥20% of CO<sub>2</sub> emission came from soil cultivation and agricultural practices. Today, scientists concerned with agricultural sustainability and soil quality continue to accumulate data on SOC changes in crop and grazing land soils.

Much less studied than CO<sub>2</sub> and nearly 300 times more potent in global warming potential is N<sub>2</sub>O. Human activities have more than doubled the rate of transfer of the highly abundant, but biologically unavailable, dinitrogen (N<sub>2</sub>) to biologically available forms of N (i.e., NH<sub>4</sub>, NO<sub>3</sub>). Estimated global N fixation in 1995 from natural and agricultural biological N fixation, NO<sub>x</sub> combustion, and synthetic fertilizer manufacture was ~260 Tg N year<sup>-1</sup> (Galloway et al., 1995). Industrial fixation of N for fertilizer from 1995 to 2001 ranged from 86 to 90 Tg N year<sup>-1</sup> (FAO, 2004). Enrichment of atmospheric N<sub>2</sub>O concentration from circa 1850 to 2002 was ~30 ppbv (from 289 to 318 ppbv) (Enquete Commission, 1992; WDCGG, 2004). Human-induced emission of N<sub>2</sub>O is presently increasing by ~150 Tg N year<sup>-1</sup>. The need to feed (~125 Tg N) and provide energy (~25 Tg N) for the growing world population drives this increase in demand for fixed N, but it also results in increased emission of N<sub>2</sub>O (Mosier et al., 2002).

The designation of land as agricultural implies anthropogenic effects in the form of disturbance or management input for the production of food, fiber, and ornamental plants. There has been much effort by scientists to define and describe the storage of soil organic carbon (SOC) in northern temperate climates. In the past few years, scientists have focused on intensively managed croplands, because implementation of new conservation and production practices can increase rates of SOC storage. Information about GHG mitigation or contributions from grazing lands (range and pasture) and their soil's health has

developed more slowly, perhaps due to a perception that SOC in grazing lands is in equilibrium and stable with time. However, grazing lands can also be managed to increase SOC (Follett et al., 2001).

## 2. Basis for research needs

Global problems of soil degradation and contamination, pollution of natural waters, depletion of the SOC pool, increased atmospheric emissions of radiatively active trace gases, and the threat of an accelerated greenhouse effect are widely recognized around the world. Some factors that should be considered in ameliorating these problems include the following:

- Unintentional consequences of management of agricultural systems, as well as of other human populated systems and areas, often create environmental problems. However with supporting policies, agriculture could help provide solutions to various environmental problems.
- Agricultural science is addressing issues of greenhouse gas emissions and soil C sequestration, but policies to help support technology transfer and implementation would ensure success.
- Policies to address GHG emissions based on science and backed by economic justification are the best incentives for natural resource managers, industry, and other sectors to implement approaches to mitigate climate change.
- Realistic and credible goals for soil C sequestration are necessary.
- Engineering technologies and management decisions should be part of the climate change solution only after widespread and rigorous assessment of their efficacy, efficiency, and potential for unintended consequences, regardless of the sector for which they are proposed.
- Practices and policies that promote conservation of natural resources, such as soil will ensure that those resources will be available for future generations.
- The complex problem of climate change is most likely to be mitigated effectively by a mix of practices, technologies, and policies that address the problem on different scales of time and geography.

Thorough evaluation and utilization are needed of: (1) current scientific facts about the attributes of soil and natural resources, (2) strategies for sustainable use of our finite, non-renewable, and fragile land resources, and (3) advances made by agricultural sciences pertaining to soil C sequestration and GHG emissions. Implementation of current advanced technologies and improved knowledge of agroecosystem science will aid our efforts to address issues such as global climate change, sustainability of natural resources, improved fertilizer- and fuel-use efficiencies, and improved public knowledge and policies concerning the role of agriculture in contributing to and mitigating GHG emissions.

### 3. Recommended practices for soil C sequestration

A wide range of current options is available for agricultural systems to sequester atmospheric CO<sub>2</sub>. Applicability of options might differ for different soils and ecoregions, because of biophysical and socio-economic conditions. Site-specific adaptation may be needed to select the most appropriate combination of options, such as:

- adopting conservation tillage, surface-residue management, and mulch farming;
- cultivating crops with deep root systems;
- developing and cultivating plants with high lignin content, especially in residue and roots;
- replacing annual crops with perennial crops;
- eliminating summer fallow and incorporating legumes and other appropriate cover crops in rotations;
- applying animal manures and non-toxic anthropogenic biosolids;
- enhancing biological N fixation;
- increasing crop biomass production;
- using N more efficiently through integrated nutrient management and precision farming;
- increasing SOC in sub-soil layers (deep in the profile) through best management and other techniques;
- managing range lands and pastures with improved grazing, vegetation management, fire management, and other best management practices;

- conserving soil and water resources;
- using water more efficiently through drip irrigation, water harvesting, and other measures to conserve water;
- restoring marginal and degraded lands through revegetation, afforestation, and rejuvenation, or simply protecting existing perennial cover;
- managing land to prevent loss of soil inorganic carbon (i.e., carbonates);
- managing high water table by blocking drainage in fall and winter;
- removing organic soils from cultivation.

### 4. Recommended practices for reducing N<sub>2</sub>O emission

Nitrogen is ubiquitous in the environment. It is one of the most important nutrients and is required for the survival and development of all living organisms. It is essential for protein synthesis in plants, animals, and microorganisms. Nitrogen accounts for 78% of the atmosphere in the form of N<sub>2</sub>. Some of the most mobile substances found in the soil–plant–atmosphere system contain N and their transport and transformations as reactive forms of N in the environment have been the subject of numerous reviews and books (Keeney, 1982; Follett, 1989; Power and Schepers, 1989; Follett et al., 1991; Mosier et al., 1998; Mosier, 2001a,b; Laegreid et al., 1999; Follett and Hatfield, 2001).

Microbial processes are important sources and sinks for N<sub>2</sub>O in the biosphere. Many groups of microorganisms are capable of producing N<sub>2</sub>O. It is likely that most biological processes involving the oxidation or reduction of N through the +1 (N<sub>2</sub>O) and the +2 (NO) oxidation states can produce trace amounts of these N gases. Bacterial processes of denitrification and nitrification are the dominant sources of N<sub>2</sub>O in most natural systems. Only denitrification to N<sub>2</sub> is recognized as a significant biological consumptive fate for NO and N<sub>2</sub>O.

As with the mitigation of CO<sub>2</sub>, current and improved conservation technologies offer a range of options for agricultural systems to decrease N<sub>2</sub>O emission. Options may differ for different soils and ecoregions. Site-specific adaptation may be needed to select the most appropriate combination of options, such as:

- improving fertilizer N-use efficiency with better timing, placement, and prediction of required N;
- synchronizing N fertilizer application with plant demands throughout the growing season;
- minimizing water movement across the soil surface and below the crop root zone;
- accounting for weather predictions before N application to help minimize N transport or loss;
- scheduling irrigation for more effective nutrient utilization;
- using slow-release inorganic and organic N fertilizers;
- using chemical additives to inhibit N mineralization;
- using cover crops or deep-rooted crops for scavenging residual N;
- testing soil and fully accounting for N in manure, residue, and residual soil N;
- selecting plant genetics to improve plant N-use efficiency;
- managing feedlots to minimize nitrification and leaching of nitrate;
- applying organic amendments to soil at rates and times based on agronomic principles.

## 5. Current limitations to reducing CO<sub>2</sub> and N<sub>2</sub>O emissions by agriculture

The exponential growth of global human population is placing increased demands on agriculture to produce more food and fiber. World population has grown by one billion people in the past 12 years, exceeding 6 billion in 2000, and is projected to reach 9 billion by 2050 (USCB, 2004). More than 90% of this growth has been taking place in developing countries, in sharp contrast to Western Europe, North America and Japan, where population growth is small or stagnant. The USA is the only industrialized country in the world where large population increases are projected, partly as a result of immigration. The population of the USA in 2000 was estimated at 281.4 million with annual growth of ca. 1%. By 2050, population of the USA is projected at 403 million people (USCB, 2004; USPRC, 2004).

Increasing demand for food by the growing global population is resulting in increased soil disturbance, increased fossil fuel consumption to produce agricultural products, and increased biomass burning.

Globally, land area devoted to permanent crops was 130.4 Mha in 2001, which was an increase of  $\sim 1.1$  Mha year<sup>-1</sup> since 1995 (FAO, 2004). In the USA, land in permanent crops was 1.41 Mha in 1997, increasing by  $\sim 0.7\%$  year<sup>-1</sup> during the previous 5 years (NASS, 2003). Diversion of additional land for crop cultivation would be accompanied with some land disturbance and potential GHG emission. The CO<sub>2</sub> emission resulting from off-farm N fertilizer production associated with crop production in the US was estimated at 9.4 Tg CO<sub>2</sub>-C equivalent (Lal et al., 1998). In 1998,  $\sim 13.5$  Tg of N fertilizer was produced in the USA, and 88.4 Tg was produced globally increasing by 0.56 Tg year<sup>-1</sup> (FAO, 2004). These amounts and rates of N fertilizer produced suggest that  $\sim 62$  Tg CO<sub>2</sub>-C equivalent year<sup>-1</sup> are emitted globally and this rate is increasing by 0.4 Tg CO<sub>2</sub>-C equivalent year<sup>-1</sup>.

The CO<sub>2</sub> emission from farm machinery use to produce food and fiber for the growing world population is another agricultural GHG source. Farm energy use on cropland in the USA was estimated at 9.2 and 3.5 Tg CO<sub>2</sub>-C equivalent for diesel and gasoline, respectively (Lal et al., 1998). There are  $\sim 4.8$  million tractors in the USA and worldwide there are 26.8 million agricultural tractors (FAO, 2004). Assuming a similar rate of CO<sub>2</sub> emission from tractors in the USA (12.7 Tg CO<sub>2</sub>-C equivalent for 4.8 million tractors), then CO<sub>2</sub> emission from tractors in the world would be  $\sim 71$  Tg CO<sub>2</sub>-C equivalent. Recognizing that agricultural tractors in the USA are likely larger than in other countries, worldwide emission of CO<sub>2</sub> from agricultural tractors would be somewhat  $< 71$  Tg CO<sub>2</sub>-C equivalent, but still large.

Inefficient plant nutrient use and cycling, especially for N, potentially occur for agricultural systems where livestock products are produced. For example, several key obstacles make improvements in manure management difficult and costly, keeping nutrient cycling in animal agricultural systems less than ideal. One obstacle is high animal density that occurs in feedlots and confined animal feeding operations, leading to a shortage of nearby land to which manure can be applied for effective nutrient utilization (Ribaud et al., 2003). Similarly, human concentration in cities creates a large reservoir of nutrients in sewage sludge that, if land disposal is chosen, may not be effectively utilized on the limited agricultural land nearby. Large

confined animal feeding operations and the development of regional specialization in poultry, dairy, and other animal production operations has created situations where more manure and associated nutrients are produced than can be effectively used. These current obstacles to nutrient efficiency are great opportunities for research and development.

Although ammonia ( $\text{NH}_3$ ) is not a direct GHG, its transformations in the biosphere do contribute to global warming potential. Domestic animal excreta, synthetic fertilizers, and biomass burning are responsible for  $\sim 40$ , 17, and 11% of global  $\text{NH}_3$  emission, respectively (Mosier, 2001a,b). Atmospheric  $\text{NH}_3$  can be taken up by soils and converted to  $\text{NH}_4^+$  in the presence of water, which can then lead to trace gas production of  $\text{N}_2\text{O}$  (Fig. 1). Consequently, the processes of  $\text{NH}_3$  emission from livestock production systems, its uptake by soil, and subsequent production of  $\text{N}_2\text{O}$  are highly important to understanding total  $\text{N}_2\text{O}$  emission to the atmosphere. Research and development of technologies to mitigate any or all of the undesirable steps in the cycling of N are needed.

Economics of current and alternative management play a role in the type and rate of adoption of improved conservation technologies aimed at reducing GHG emissions. Several factors that will need to be considered in the future, include: (i) the rate of C sequestration or GHG mitigation, (ii) the price offered for adopting various practices, (iii) the ease with which producers and land managers can alter land use and management activities, (iv) the potential impacts of targeting regions or practices, (v) the ancillary benefits to soil, water and air quality upon adoption of practices to sequester C or mitigate GHG emissions, and (vi) the effectiveness and efficiency of various policies (Sperow et al., 2002). Farmers and ranchers, first and foremost, need to make a profit, so they will need to maintain or increase their financial situation if

they are to adopt C sequestration or GHG mitigation practices.

## 6. Scientific foundation for policy development

Without technological and/or behavioral intervention, atmospheric concentration of GHGs will continue to increase as the food and fiber needs of a growing human population are met. The USA is the third most populous nation in the world following China and India and is both a major food producer and emitter of GHGs. Market-based and/or other policy mechanisms are necessary to reduce GHG emissions from agriculture.

Good land stewardship should be supported by society so that ecological function of our bountiful and treasured landscape can be optimized for generations to come. Policies for adopting best management practices on farms and ranches will have numerous benefits to the environment and agricultural production, independent of any judgment regarding the immediacy of climate change. Soil C sequestration has great potential to help restore soil, air, and water quality even if the global climate does not change, and it will be needed even more in the event that the global climate does change. Improvements in nutrient management and N-use efficiency are needed not only to sustain a strong and viable food production economy, but also to protect our natural resources and improve the quality of land and water. Relevant and important issues were identified in the book “Soil and Water Quality: An Agenda for Agriculture” (NRC, 1993), and mitigating GHG emissions from agriculture is a worthy addition to those issues. It is increasingly important that a dialogue be developed and nurtured to address and evaluate: (i) agricultural contributions to GHG emissions, (ii) the potential of agriculture to mitigate GHG emissions, (iii) specific and broad management changes to agricultural production, and (iv) opportunities for agricultural scientists and practitioners, among others, to help provide relevant information to policy makers and agricultural practitioners, in order for them to encourage adoption of land management practices that can reduce GHG emissions and provide other benefits to farming systems and the environment as a whole. Soil C sequestration is a GHG mitigation process that should be considered among the wide array of effective responses

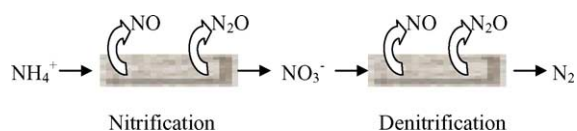


Fig. 1. A conceptual model of two levels of trace gas N production via nitrification and denitrification: (a) flux of N through process pipes and (b) holes in the pipe, through which, trace gases leak (Firestone and Davidson, 1989).

to global change (Lal et al., 2003). The global role of N as both a key building block in all ecological systems and as a water and air pollutant creates a complex societal problem, a science-based solution to which will require a sustained dialogue among policymakers, scientists, agricultural practitioners, and affected stakeholders (Follett and Hatfield, 2001). In general, the more complex is the natural resource issue, the longer and more deliberative the process necessary to craft legislation and as described by Reed (2002), “In the case of issues with a complex scientific underpinning, such as climate change, the deliberative process demands a (more) thorough, thoughtful interface between scientists, who tend to speak in terms of ‘uncertainties’, and policymakers, who seek the bottom-line ‘certainties’ necessary to create good policy and prudent laws”.

## 7. Research needs

An oriented vision among scientists is often difficult to achieve without national planning and patient leadership. Equally difficult to develop is an integrated and focused approach to achieve desired outcomes. These statements are made in the context of the scientific expertise and long-term committed resources needed to address the increasingly complex issue of agricultural sustainability by balancing productivity, profitability, environmental quality, and social responsibility at local, regional, national, and global levels. A strong scientific underpinning is now available concerning the potential of terrestrial ecosystems, including agroecosystems, to sequester atmospheric CO<sub>2</sub> into plant biomass and soil organic matter and minimize GHG emissions through improved management practices, which can simultaneously improve soil and water quality. In addition to research on currently recommended practices mentioned before, we propose a list of research needed to further advance our understanding of soil C sequestration:

- develop agricultural systems that minimize net global warming potential;
- investigate C, N, P, and S cycles together for total ecosystem management;
- simultaneously characterize the effects of various agricultural systems on soil C sequestration and off-

site impacts, such as water quality from nutrient leaching and sediment transport;

- develop agricultural systems to produce energy crops (i.e., biofuels) and sustain or improve soil and water quality;
- quantify the contribution to SOC from below-ground versus above-ground plant biomass of different plant species and develop harvest management systems less degrading to soil;
- quantify the effects of soil physical and chemical characteristics (e.g., clay composition, Fe, Ca, etc.) on soil C sequestration;
- determine the role of soil microbial community composition and activity on biogeochemical cycling of C and N;
- quantify rhizodeposition as a contributing factor in C and N transformations;
- quantify factors affecting soil inorganic carbon pools and transformations;
- conduct more long-term field studies (>10 years) to investigate whole-ecosystem responses;
- develop accurate, easy-to-use, simulation models to describe SOC sequestration in important agricultural systems and that are accepted by action and regulatory agencies at scales ranging from field to farm to local to regional to national;
- develop remote sensing techniques to determine baseline and validation measures of C stocks in the near-surface soil at field or farm scale;
- develop remote sensing technologies to determine land use, cover type, and biomass at field or farm scale;
- develop better understanding and quantification of how nutrient and water management affect the potential of cropping systems to sequester SOC;
- conduct research on integrated farming systems to promote better cycling and utilization of nutrients;
- develop improved sampling and analytical methods for rapid, accurate soil C determination that can assess both spatial and temporal variability.

During the past century and a half, biological scientists have concentrated on unraveling the biological and physical–chemical intricacies of N. We now know how N moves and changes form at rates varying from milliseconds to centuries, how it moves through nature’s compartments (atmosphere, soil, water, and living matter), how it changes oxidation status under



varying environmental conditions, and how it interacts with various other elements. Despite this knowledge “nature, in its clever way, has kept science from tracking precisely the actual ledger of this whimsical element and curiously of predicting the impact of N on the environment when it accumulates at levels far above that for which stable ecosystems have adapted” (Keeney and Hatfield, 2001). In addition to research on currently recommended practices mentioned before, we propose a list of research needed to further advance our understanding of trace gas emission of N:

- investigate C, N, P, and S cycles together for total ecosystem management;
- assess major agricultural systems (high value crops, field crops, confined animal feeding operations, pastures, rangeland, etc.) for total and seasonal N<sub>2</sub>O emission;
- assess major waste management systems (animal manure, biosolids, agricultural byproducts, biomass burning, etc.) for their potential to contribute indirectly and directly to N<sub>2</sub>O emission and to be able to aggregate this potential to a national scale;
- develop accurate, easy-to-use, simulation models to describe N<sub>2</sub>O emission from important agricultural systems and that are accepted by action/regulatory agencies at scales ranging from local to national;
- develop remote sensing technologies to determine the rate, timing, and location of N<sub>2</sub>O emission in various agricultural systems;
- develop sustainable and productive agricultural systems that also minimize N<sub>2</sub>O emission and net global warming potential;
- develop improved and simplified sampling techniques to determine baseline and validation measures of N<sub>2</sub>O emission from agricultural systems;
- develop remote sensing techniques to determine baseline and validation measures of N<sub>2</sub>O emission from agricultural systems at field or farm scale.

## 8. Conclusion

There are complementarities among many of the practices and research needs stated throughout this manuscript. Besides mitigating CO<sub>2</sub> emission, sequestration of SOC has the potential to increase agricultural production and provide ancillary environmental benefits to soil and water quality. Therefore,

many of the suggested management practices may well become part of more comprehensive conservation programs. An overarching research need is to determine the multiple benefits and trade-offs of conservation technologies so that land managers can best systematically meet production and environmental goals and so that legislators can devise the most effective policies.

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Received 2 April 2004; received in revised form 6 January 2005